STAR R&D Proposal December 2013

Prototyping for STAR Forward Tracking System

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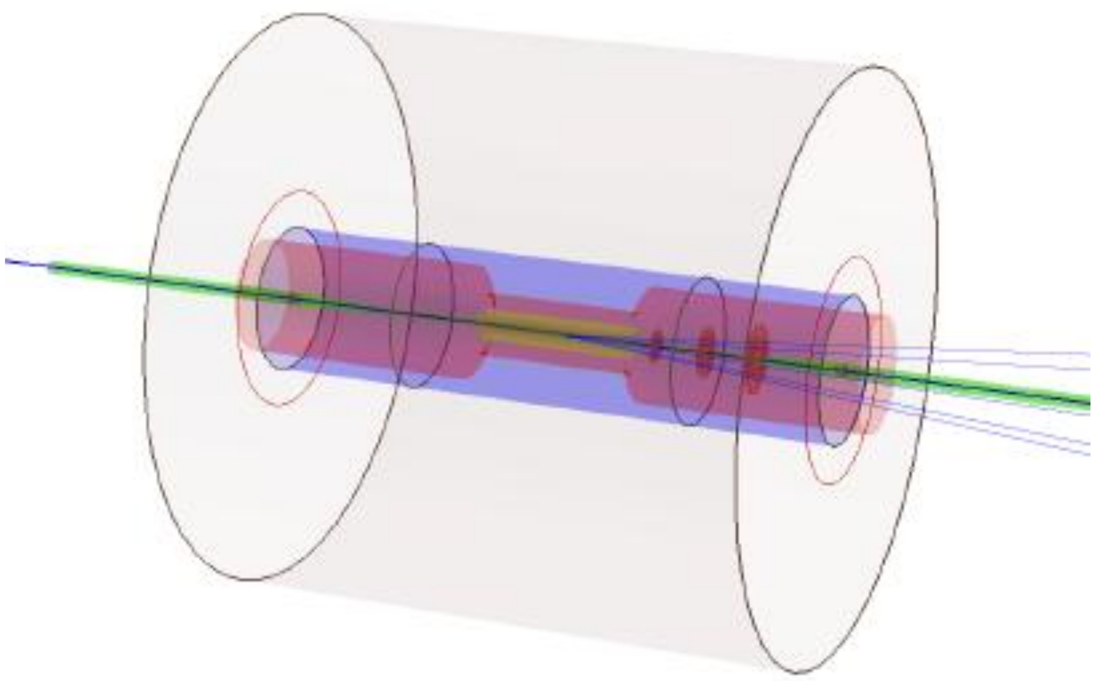
Abstract

We propose an R&D program for a forward tracking system (FTS) upgrade based on Silicon detector technology for the STAR experiment at RHIC. The proposed R&D efforts will be focused on development of Silicon Ministrip sensors and identification of suitable front-end readout chips for the FTS upgrade project. The goal is to assemble and test prototype modules to validate and optimize such a Silicon-based FTS design for future STAR physics programs.



1. Introduction

The STAR collaboration is looking into an instrumentation upgrade that will provide particle tracking and calorimetry in the forward direction[1]. Combined will other upgrades (see Figure 1), it will allow STAR to perform physics measurements with photons, electrons, muons, hadrons and jets in polarized p-p and p-A runs after 2020 and e-p and e-A runs after 2025, which are under serious consideration by Brookhaven National Laboratory[2]. These measurements can provide valuable information about nucleon spin structure such as parton helicity distributions and transversity functions, on-set of gluon saturation at small x, as well as cold nuclear matter effect in nucleus collisions[3]. Therefore it is really important that STAR develops the ability to measure at large rapidity regions ($2.5<\eta<4$) unidentified charged hadrons, identified hadrons (π^0, Λ), direct photons, e^+e^- pairs from Drell-Yan production, di-hadron/jet and photon-hadron/jet correlations.

The forward tracking is expected to play an essential role in the abovementioned physics programs to provide charge-sign separation through track curvatures and photon identification through hit-on-road measurement. We will show below that a Forward Tracking System (FTS) consisting of three or four Silicon Ministrip planes can meet the above expectation. Moreover, despite the fact that STAR has only a 0.5T solenoid magnet, the proposed FTS could also provide a limited momentum resolution and thus help with electron-hadron discrimination through energy-over-momentum measurement. In order to be able to validate and optimize the design for such a Silicon-based FTS, we propose an R&D program in this report.

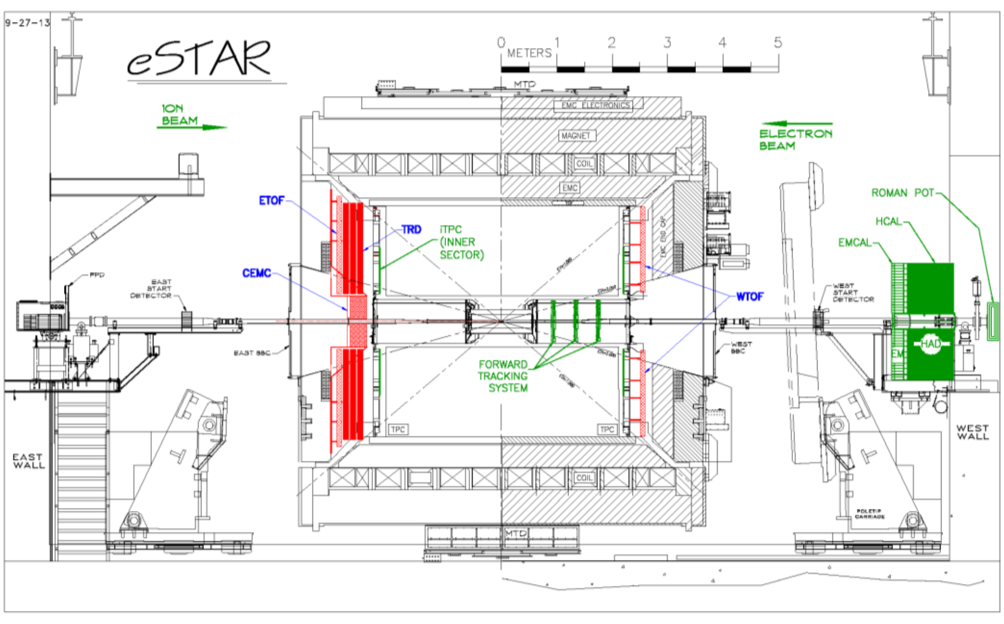


Figure 1 Cross-sectional view of the STAR detector in the EIC era[1]. Upgrades (shown in color) to the existing STAR detector include TPC inner section (iTPC), a forward tracking system, a forward calorimeter system including both EMCAL and HCAL sections, and Roman Pot Stations, which are to be completed before 2020, and a Central Electromagnetic calorimeter (CEMC), a Transition-Radiation Detector (TRD), East and West Time-of-Flight detectors (ETOF/WTOF), to be completed before 2025.

2 Goals and Timescale of the R&D Project

The goal of the proposed R&D project is two-fold: (1) to develop Silicon Ministrip sensors and (2) to identify suitable front-end readout chips for the Silicon-based FTS. The timescale to achieve this goal will be 1.5-2 years, starting from when the requested funding support becomes available. At the end of the R&D project, we expect to be able to assemble and test prototype modules so that ultimately the performance of integrated prototype modules can be examined in test-beam tests. This will help us to move towards a more complete detector system design by 2016.

3 A Silicon-based Forward Tracking System

As described in Section 1, the FTS should provide charge-sign separation and photon-electron discrimination. The former requires that the FTS have very good spatial resolution, while the latter calls for low material budget in the acceptance. It is well known[4] that carefully designed Silicon-based detectors can meet such requirements, thanks to their unique properties that are not available with other type of detectors: the combination of extremely precise measurement with high readout speed; direct availability of signals in electronic form; the simultaneous precise measurement of energy and position; and the possibility of integrating detector and readout electronics on a common substrate.

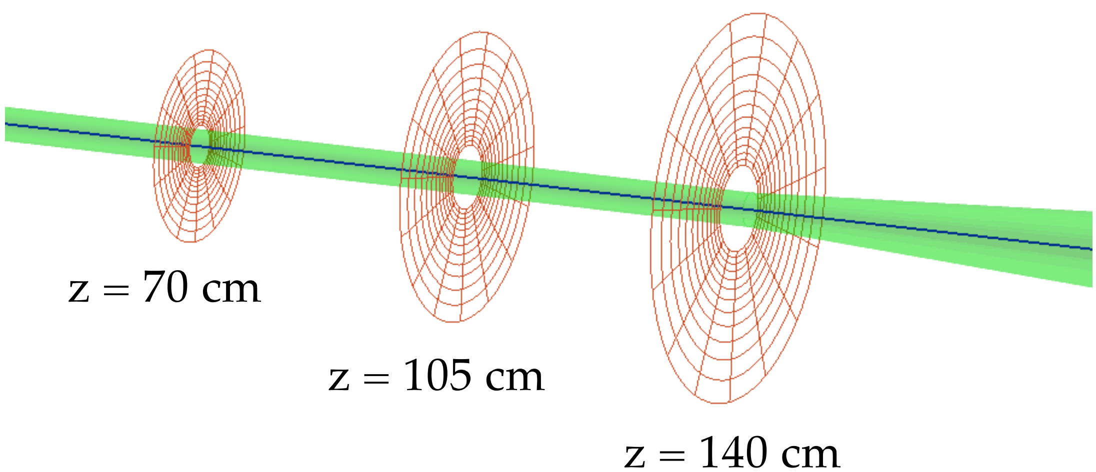


Figure 2 Layout of a Forward Tracking System consisting of three Silicon Ministrip planes located at Z=70 cm, 105 cm and 140 cm respectively. Each of the planes include 12 wedges, each of which has 128 strips in ϕ at a fixed radius and 12 strips in radial direction at a fixed ϕ value.

The FTS under consideration will be made of three to four Silicon detector planes. A layout of a Silicon-based FTS that has been studied in simulations (see Section 4) is shown in Figure 2, where three detector planes are located at Z=70, 105 and 140 cm, respectively[a]. Each of the three planes has 12 wedges covering the full 2π range in ϕ and 2.5-4 in η. A wedge has 128 (ϕ) times 12 (η) strips and provides a ϕ-

[a] Optimization of the layout is still going on.

resolution of around 1.2 mrad and a η-resolution of about 0.036[b]. Depending on the Z location, a 30-degree wedge will be made of one or two Silicon Ministrip sensor to be read out by frontend readout chips from the outer radius edge (see Figure 3). Compared to the configuration of reading out from the sensor edges along the radial direction such as PHENIX FVTX[5], the material budget in the detector acceptance will be much smaller since the frontend readout chips, power and signal buses and cooling lines will be put outside of the detector acceptance. This configuration requires a second-metal layer in the Silicon sensors in order to bring the signals from the first metal layer of AC-coupled strips to the outer radius edge of the sensor (see Figure 3). It adds complexity and cost into sensor design, fabrication and characteristics. Hence it is both necessary and important to perform R&D studies to validate and optimize such a design.

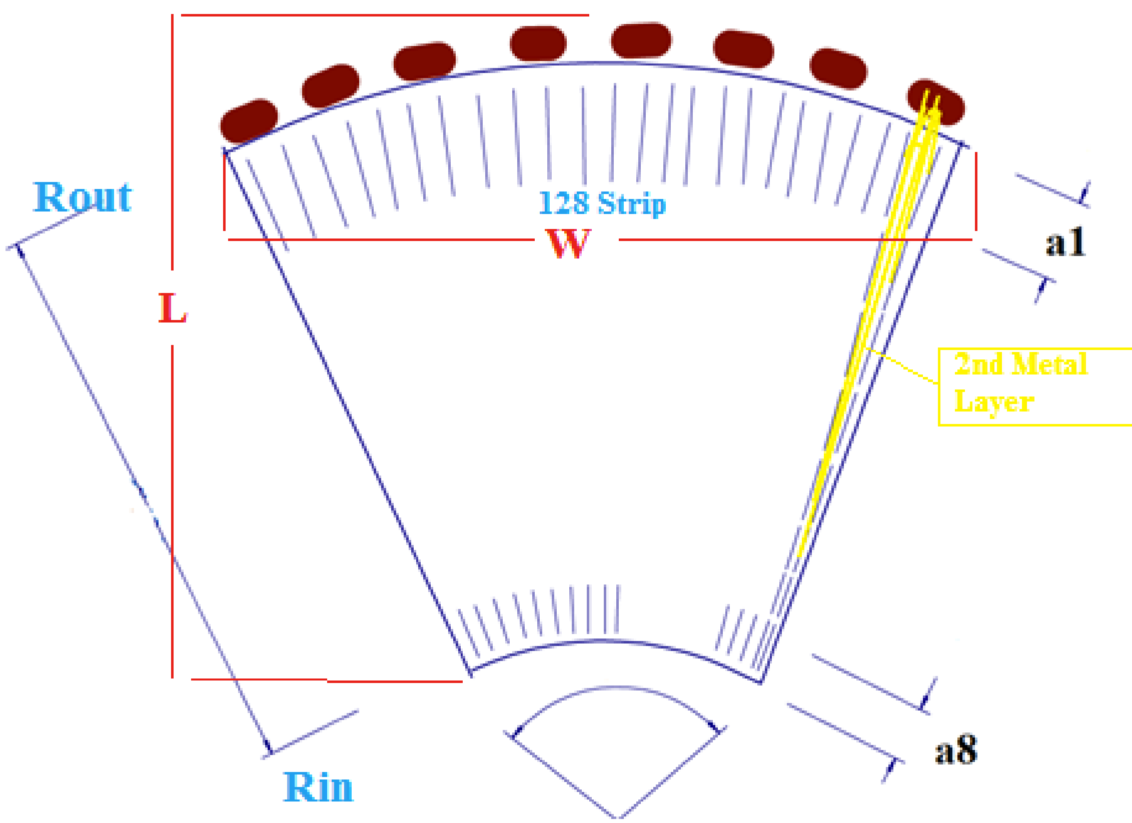


Figure 3 Schematic view of a 30-degree wedge. It consists of a Silicon Ministrip sensor with 128*12 strips, and is read out by 12 frontend readout chips.

[b] These are referred to as *reference resolutions* in the following.

4 Simulation

We have performed Monte Carlo (MC) simulations to test the FTS shown in Figure 2 for the physics requirements. Single particles were emitted from Z = 0 cm for different momenta and pseudo-rapidity. The particles were tracked through the full STAR magnetic field in the forward region and the intersection points of the tracks with the detector planes were calculated. Multiple scatterings in the material including air, beam pipe and detector material[c], were taken into account, separately for every detector hit. The detector hits were furthermore smeared in 2D with a flat distribution according to the Silicon Ministrip geometry described in Section 3.

We implemented a simple hit-matching algorithm. We first calculated for every detector plane the distance between a linear extrapolation from the previous planes, or the primary vertex respectively, to the next plane. The distance between the hit point and the extrapolated point is plotted in Figure 4 for the second and third plane as a function of the radius to the beam line. The dashed lines include all distances between extrapolated and hit points. They were used to determine the hit-matching window as a function of the hit distance to the beam line, as shown in Figure 5.

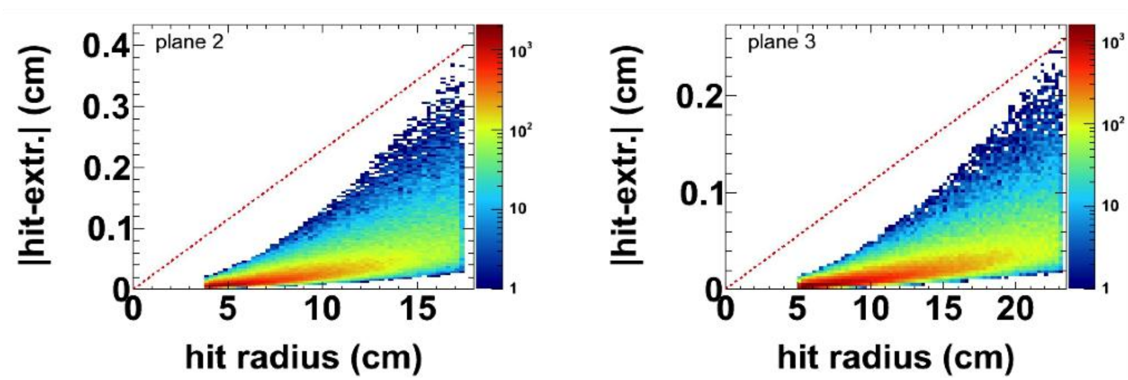


Figure 4 Distance between linear extrapolation points and hits points as a function of the hit radius to the beam line for the second (left) and third (right) plane.

The transverse momentum was reconstructed for tracks with all three hits points available plus a primary vertex with an x-y vertex resolution of 200 microns. Figure 6 shows the resolution of the inverse transverse momentum, $1/p_T$, as a function of momentum, p. For p<10 GeV/c the $1/p_T$-resolution is in the range of 13-16%, and it rises to about 40% around p=80 GeV/c. As $1/p_T$-resolution is primarily sensitive to the ϕ-resolution in a solenoid magnetic field, we systematically studied how the ϕ-resolution affected the $1/p_T$-resolution by changing the ϕ-resolution between 0.5 to 4.5 times the reference ϕ-resolution (see page 4). We found that $1/p_T$-resolution did

[c] We have made a conservative assumption that the radiation length per detector plane is 1.2% X_0, which is the material budget for the STAR IST. But as discussed in Section 3, the frontend readout chips, power and signal buses and cooling lines will be put outside of the detector acceptance, the final material budget in detector acceptance could be much smaller compared to the value assumed here.

not get better when we increased the resolution to better than 0.9 of the reference resolution. This can be understood as multiple scattering effect started to dominate over the intrinsic detector resolution. We conclude that the reference ϕ-resolution is close to the optimal for getting the best $1/p_T$-resolution, which provides a useful input to e-h discrimination through energy-over-momentum measurement[6].

We have also studied the charge-sign separation. Shown in Figure 7 are distributions of reconstructed transverse momentum for positively and negatively charged particles with 40 GeV/c momentum at η=3.5. As can be seen, a clear separation between the two distributions is achieved. We further studied the charge-sign purity for p=80 GeV/c particles at η=3 as a function of the ϕ and η resolutions, as well as for different radiation lengths, as shown in Figure 8. Here the charge-sign purity is defined as the fraction of positively charged particles falling into the 2.5σ window (see Figure 7) of negatively charge particles, or vice versa. As can be seen, the charge-sign purity is close to 1 for ϕ-resolution equal or better than the reference resolution, whereas it drops for larger ϕ-resolution. The η-resolution and X_0-dependence is almost negligible.

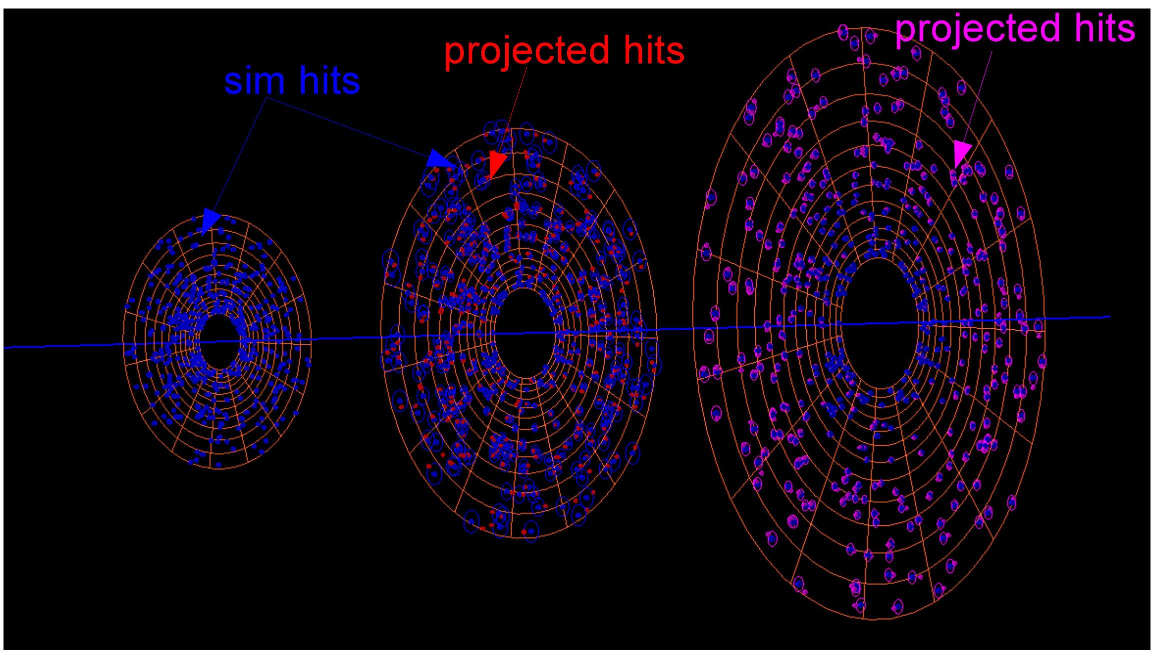


Figure 5 Illustration of the tracking and hit-matching procedure. Blue points are calculated hit positions, red and magenta points are linear extrapolations from the previous planes. Small circles indicate the hit-matching window.

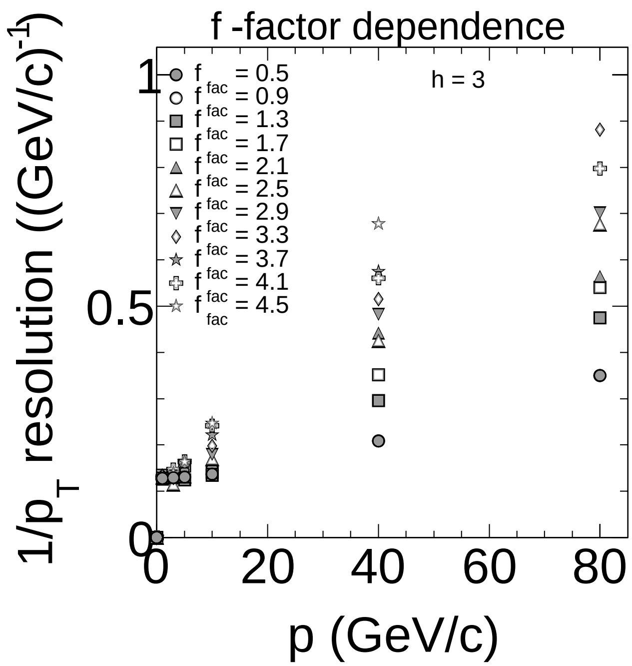


Figure 6 Left: Inverse transverse momentum resolution as a function of track momentum at η=3 for various ϕ resolutions, e.g. ϕ_{fac} is the ratio of the ϕ resolution relative to that of the reference design of 128 strips in ϕ per 30-degree wedge.

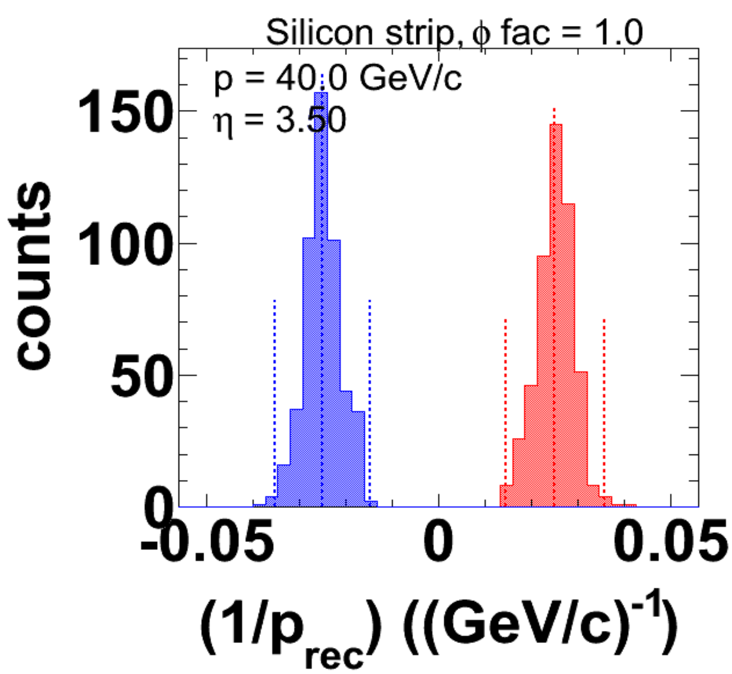


Figure 7 Distributions of reconstructed inverse transverse momentum for positively (red) and negatively (blue) charged particles with a momentum of 40 GeV/c at η=3.5. The vertical dashed lines indicate the position of 2.5σ resolution. The simulation was done with the reference ϕ-resolution.

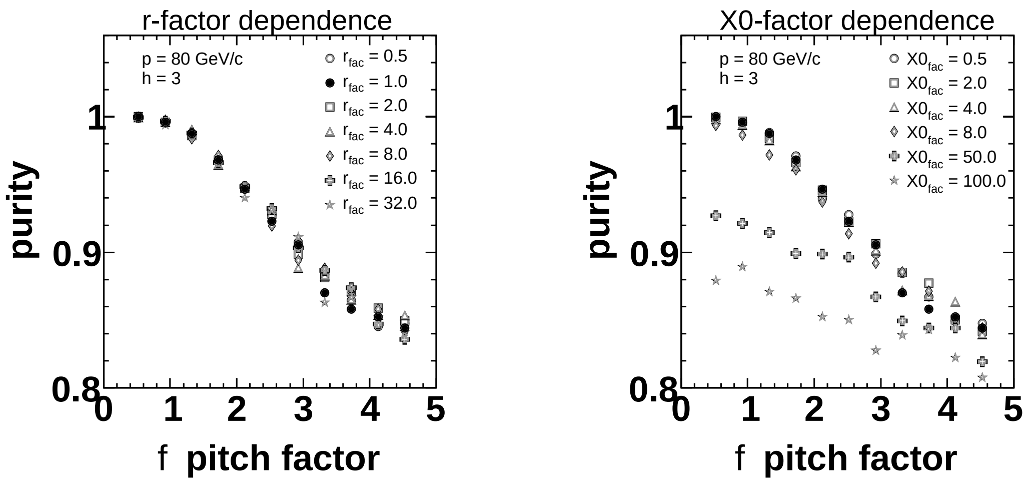


Figure 8 Left: charge-sign purity for different ϕ and η resolutions (all relative to reference resolutions described in page 4). Right: charge-sign purity for different radiation lengths (relative to a reference material budget of 1.2% X0 per plane. For example, X0fac=0.5 means that each plane has a radiation length of 0.6% X0).

5 Prototyping

As explained in Section 3, it is necessary and important to develop Silicon sensors utilizing a double-mental layout structure in order to reduce the material budget. It is also important to identify suitable frontend readout chips, which will affect the overall performance and design of the detector. We plan on assembling and testing prototype modules, each of which corresponds to a 30-degree wedge as described in Section 3. A module will have a Silicon sensor with frontend readout chips mounted on and supported from a FR4 PCB frame.

We have developed a preliminary sensor mask layout (see Figure 9) and received a preliminary quote from a vendor. Further discussions with the vendors will be needed in order to finalize the sensor design, which could take a couple of months. The delivery time after the final sensor design becomes available will be another 4-6 months, which gives a total lead-time of more than half a year for the sensors.

We will assemble a test DAQ system based on FlexRIO system from National Instructions, which allows one to read out and compare prototype modules with different frontend readout chips on the markets such as APV, FPHX, FSSR or SVX4 chips. This will add into the total cost compared to the case that we read out the prototypes using APV chips and existing DAQ system developed for the STAR IST detector[d]. As APV chips are not being produced anymore and become less and less available, it is very unlikely that they can be used for the final FTS production. Hence it is really important to start looking into other readout chips and getting experience with them rather soon.

[d] Difference can be found by comparing Table 1 and Table 2.

Finally, we have discussed with Fermilab Silicon Detector Facility group about prototype assembly and confirmed that they are willing to provide the service, should such a service be needed in the abovementioned timescale.

After the requested funding becomes available, we expect that it will take about ½ year to obtain the Silicon sensors. It will take another ½ year to develop the DAQ system with the FlexRIO system and have prototype modules assembled. The last step in the proposed R&D program is to test the assembled prototypes using radiation sources, Laser and Cosmic rays in the UIC Siliocn Detector laboratory and ultimately in Fermilab test beam. Thus the full R&D program could take 1.5-2 years.

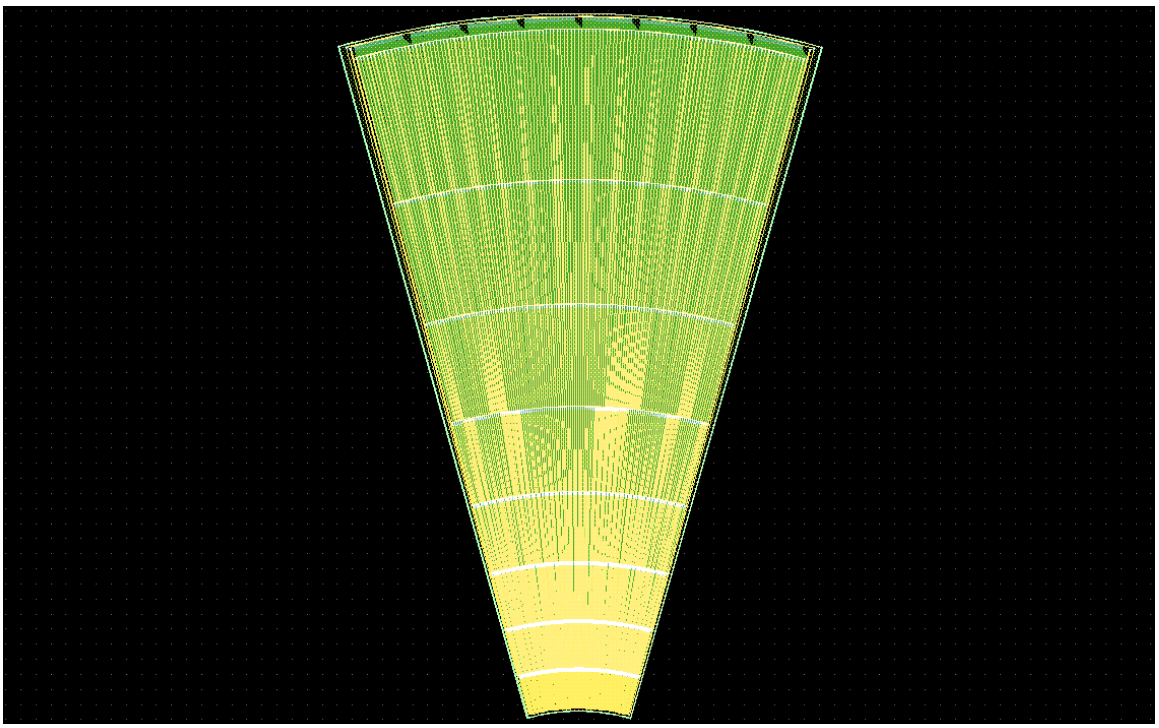


Figure 9 Preliminary sensor mask layout.

6 Institutions and Personnel

Personnel involved in this R&D program will primarily be Prof. Ye, Dr. Abi and Wang from University of Illinois at Chicago (UIC), and Dr. A. Schamah from Lawrence Berkeley National Laboratory (LBNL), with the Principle Investigator (PI) being Ye from UIC. The UIC group has a Silicon detector Laboratory including cleanroom and test equipment used for STAR IST project and on-going R&D project on Active Edge Silicon sensor development in collaboration with Fermilab Silicon detector R&D group. The PI, Ye from UIC, has multiple years of experience in Silicon detectors, including Dzero Silicon Microstrip Tracker operations and radiation damage studies, R&D for hybrid Silicon pixel sensor and readout chip integration using oxide-bonding technique, and R&D for Phase-II CMS Level-one tracker trigger upgrade based on 3D integration techniques, and is currently working on the STAR Intermediate Silicon Tracker (IST) project and R&D for Active Edge Silicon sensor development. Dr. Abi from UIC has worked on ATLAS Silicon pixel detector and has multiple years of experience in electrical engineering and readout DAQ systems. Dr. Wang from UIC has been worked on the STAR IST project, leading the efforts on IST stave production QA at UIC and development of IST geometry model, simulation and reconstruction software in the STAR framework. The UIC group will be responsible for Silicon sensor development, PCB design, prototype module and DAQ system assembly and testing. Dr. Schama from LBNL has been working on simulations described in Section 4 and will continue such an effort towards an optimized detector layout.

7 Summary

We propose R&D studies for a Silicon-based Forward Tracking System (FTS) for STAR, which will be essential for STAR p-p, p-A, e-p and e-A programs. Through simulation studies, we have found that such a FTS seems to give the best performance in terms of charge-sign separation, photon identification, as well as momentum resolution. The proposed R&D studies will be focused on Silicon Ministrip sensor development and identification of suitable frontend readout chips, which will allow us to validate such a FTS design concept and move towards a more complete detector system design. The total budget request is given in Table 1. The R&D funding needs to be provided as soon as possible as some of the components have a lead-time of a few months.

We note that there are areas that are not covered in this R&D proposal, including mechanical structure and backend readout electronics. The former will require efforts integrated within the full STAR upgrade plan by the STAR collaboration while the latter can only be done after the frontend readout chips have been chosen, which will need to be looked into in 1-2 years or so.

7 Budget Request

Silicon Sensor Mask Design and Procurement ($30k+$5.4k*10)	$84.0k
Frontend Readout Chip Procurement	$4.7k
PCB Design and Procurement	$25.0k
Electronics (DAQ, test setup and test run equipment)	$45.0k
Prototype Module Design and Assembly (with 26% overhead)	$20.2k
Machine and Electronics Shop (with 26% overhead)	$25.2k
Travel (with 26% overhead)	$12.6k
Shipment (with 26% overhead)	$6.3k
Total Direct Cost	$201.6k
Total Indirect Cost	$21.4k
Total Cost	$223.0k

Table 1 Budget request to develop Silicon Ministrip sensors and identify suitable frontend readout chips.

Silicon Sensor Mask Design and Procurement ($30k+$5.4k*6)	$62.4k
Frontend Readout Chip Procurement (CHF15*108)	$1.9k
PCB Design and Procurement	$10.0k
Electronics (DAQ, test setup and test run equipment)	$10.0k
Prototype Module Design and Assembly (with 26% overhead)	$12.1k
Machine and Electronics Shop (with 26% overhead)	$15.1k
Travel (with 26% overhead)	$12.6k
Shipment (with 26% overhead)	$6.3k
Total Direct Cost	$115.9k
Total Indirect Cost	$14.5k
Total Cost	$130.4k

Table 2 Budget request to develop Silicon Ministrip sensors read out with APV chips.

References

[1] eSTAR: a Letter of Intent, STAR collaboration, (2013).
[2] BNL's plan for completing the mission of RHIC and the transition to eRHIC (2013).
[3] Electron Ion Collider: the Next QCD Frontier, A. Accardi et al., arXiv:1212.1701.
[4] See e.g. Semiconductor radiation detectors, G. Lutz (1999).
[5] PHENIX FVTX technical design report.
[6] Yuxi Pan, presentation at the eSTAR meeting.